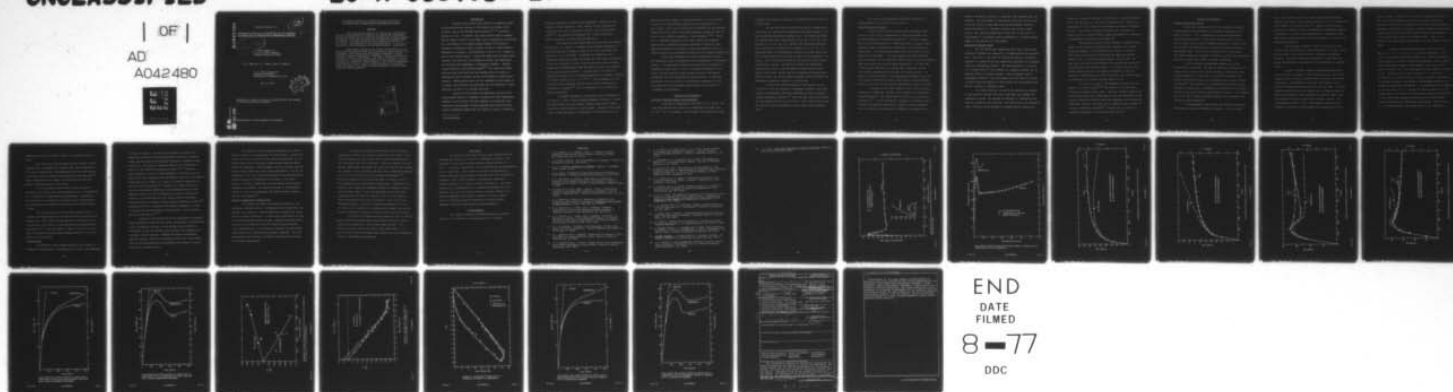


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DEFORMATION BEHAVIOR OF POLYETHYLENE AND POLYCARBONATE IN TENSILE--ETC(U)  
JUN 77 W A SPITZIG, R J SOBER, O RICHMOND N00014-76-C-0855  
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DEFORMATION BEHAVIOR OF POLYETHYLENE AND POLYCARBONATE  
IN TENSION AND IN COMPRESSION AT ATMOSPHERIC PRESSURE

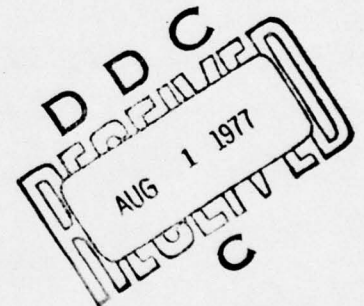
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Final Report on  
Office of Naval Research  
Contract N00014-76-C-0855

W. A. Spitzig, R. J. Sober, and O. Richmond

U. S. Steel Corporation  
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Monroeville, Pennsylvania 15146

June 30, 1977



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Deformation Behavior of Polyethylene and Polycarbonate  
in Tension and in Compression at Atmospheric Pressure

Abstract

The stress-strain behavior of high-density polyethylene and Lexan polycarbonate was examined in tension and compression. The results showed that for both the polyethylene and polycarbonate tested, the yield and flow stresses in compression exceeded those in tension, a phenomenon known as the strength differential or S-D effect. The magnitude of the effect was about  $5 \pm 1$  and  $14 \pm 2$  percent for the polyethylene and the polycarbonate, respectively.

Measurements of the volume changes occurring during and resulting from plastic deformation with density determinations and dilatometer tests showed that polyethylene underwent a volume expansion, whereas polycarbonate underwent a volume contraction as a result of plastic deformation. The volume contraction in polycarbonate is in complete disagreement with the normality flow rule of plasticity theory and lends credence to our previous hypothesis, from studies on steels, that the classical theory of plasticity should be modified to include pressure-dependent yielding without requiring volume expansion.

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## Introduction

Proposed yield criteria for polymers are generally based on pressure-modified versions of the Tresca or von Mises yield criteria, such as the Coulomb yield criterion<sup>1,2,3)\*</sup> originally applied to soils. In general, the yield criteria used for metals, such as those of Tresca or von Mises, are not adequate for explaining the yield behavior of polymers because polymers are generally stronger in compression than in tension and show a large pressure dependence of yielding. (See References 2 and 4-7 for a summary of most of the previous work.) In both the Tresca and von Mises yield criteria, the yield and flow stresses in tension and compression are identical and independent of hydrostatic pressure. However, recent studies on high-strength steels<sup>8,9)</sup> have shown that these materials also have yield and flow stresses that are larger in compression than in tension and that are dependent on hydrostatic pressure. These results point out the inadequacy of the Tresca or von Mises yield criteria for describing the yield behavior in such materials, as well as in polymers and soils.

Analysis of the tension and compression results in the high-strength steels at atmospheric pressure and under hydrostatic pressures up to 1104 MPa (160 ksi) obtained in conjunction with determining the permanent volume expansions that occurred during plastic deformation showed that the classical theory of plasticity

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\* See References.



should be modified to include pressure-dependent yielding without requiring volume expansion. Such a theory has been proposed previously for the plastic deformation of soils and granular materials<sup>10,11)</sup> and suggests the potential for a general plasticity theory applicable to a wide class of materials.

The results for the steels and soils show that the pressure coefficient, "a", which is a measure of the pressure dependency of the yield and flow stresses, is about 0.01 to 0.04 for metals and about 0.25 to 0.4 for soils. To explore the possibility of a generalized plasticity theory applicable to a wide range of materials, it was felt desirable to find a class of materials with a pressure coefficient in between that found for metals and soils for analysis of the yield and flow behavior. Previous work on the effect of hydrostatic pressure on the deformation behavior of polymers indicates "a" values of about 0.04 to 0.1.<sup>2,4,6,7)</sup> It also appears that the permanent volume expansion resulting from plastic deformation is negligible in polymers,<sup>12)</sup> as it is observed to be in metals and granular materials.

A general deficiency in the previous work on polymers is the lack of a study in which pressure-dependent yielding in tension and compression and volume changes resulting from plastic deformation were investigated on a given polymer. Because of the strong effect of specimen purity, crystallinity, and orientation of the

specimen axis with respect to the draw direction, it is unrealistic to use results from different studies for the formulation of a basic theory. Also, recent studies have indicated that the pressure-transmitting fluid used in hydrostatic pressure studies can have an effect on the resultant properties of some polymers.<sup>13-15)</sup> Therefore, a meaningful analysis of the yield criteria for polymers requires that a systematic study be undertaken in which all the important parameters are measured on the same polymer and care is taken to prevent any environmental effects on the resultant properties.

This report describes the results obtained from tension and compression tests on polyethylene and polycarbonate at atmospheric pressure. The magnitudes by which the yield and flow stresses in compression exceed those in tension (strength-differential or S-D effect) and the permanent volume changes resulting from plastic deformation have been determined for both polymers. In addition, preliminary work on testing in the hydrostatic-pressure unit and the protection of the polymers during testing in the castor oil environment are discussed.

### Materials and Procedures

#### Materials, Specimen Design, and Procedures

High-density polyethylene ( $950 \text{ kg/m}^3$  or  $59.3 \text{ lb/ft}^3$ ) and Lexan polycarbonate were obtained as commercially extruded rods 25.4 mm (1 in.) in diameter. Various types of specimens were used

throughout this study but they were all machined directly from the extruded rods.

The specimens used to evaluate the effect of hydrostatic pressure on the yield and flow characteristics were designed to fit into the Harwood hydrostatic pressure unit. The tension specimens had threaded ends with a gage length of 25.4 mm (1 in.) and a gage diameter of 11.4 mm (0.45 in.), whereas the compression specimens were cylinders 25.4 mm high with a diameter of 12.7 mm (0.5 in.). Specimens tested in the hydrostatic pressure unit were coated with RTV silicone rubber which required 24 hours at room temperature for curing. This coating did not bond to the polymers and was easily removed after testing. The same size tension and compression specimens were used to evaluate density changes resulting from plastic deformation, and the same size compression specimens were used to evaluate the volume changes occurring during deformation at atmospheric pressure by testing in a dilatometer.

To obtain an accurate measure of the magnitude of the S-D effect of the two polymers at atmospheric pressure, additional tension and compression tests were performed by using a combined tension-compression specimen.<sup>16)</sup> Both the gage length and diameter of this specimen were 16.5 mm (0.65 in.), and a clip-on strain gage was used for strain measurements in both tension and compression tests.

All tension and compression tests were conducted at a crosshead motion of 0.02 mm/s (0.05 in./min).

#### Volume-Change Measurements

Volume changes resulting from plastic deformation were determined from density measurements by using the apparatus and methods developed and described previously.<sup>17)</sup> The only changes made were that the weighings in liquid were made in ethylene glycol monobutyl ether and kerosene for polyethylene and polycarbonate, respectively. The density measurements were made before and after straining the specimens. Any volume changes are those remaining after straining, that is, permanent volume changes, and not necessarily those that might have occurred during deformation. The grip ends of the tension specimens were removed after straining, and the final density determinations were made on the gage section. The amount of permanent strain of the specimens was measured during the final density measurements because some recovery occurred between the end of the test and the density determination (about two hours).

To determine the volume changes occurring during plastic deformation, compression specimens were deformed in a dilatometer containing mercury. The system used was similar to one described previously.<sup>12)</sup> In the dilatometer, a specimen is deformed inside a cylinder containing mercury and the volume of mercury displaced from the cylinder as the specimen is deformed is measured by the



height of the mercury column in a capillary tube connected with the cylinder. The displacement of the mercury column due to the motion of the ram itself is subtracted from the displacement resulting during deformation of a specimen to obtain the specimen volume change. The capillary system used is such that a 1 mm (0.04 in.) displacement of the mercury column corresponds to a relative volume change of the specimen of 0.025 percent.

#### Hydrostatic Pressure Tests

All the tension and compression tests under superimposed hydrostatic pressure are conducted in a Harwood hydrostatic pressure unit. This unit is also used for testing specimens at atmospheric pressure for comparison and for pressurizing specimens for subsequent testing at atmospheric pressure. The high-pressure unit is based on a previous design<sup>18)</sup> and consists of a pressure cylinder and two separate hydraulic pressure systems. This arrangement permits independent movement of the two pressure rams and makes it possible to control both the pressure in the cylinder and the extension rate during a tension or compression test.

For tension testing, one end of the specimen is attached to the load cell and the other end to the lower ram, whereas for compression testing, the specimen is mounted in a compression cage which is attached to the lower ram. For both tension and compression tests, straining of the specimen is accomplished by lowering the

bottom ram. Motion of the ram is controlled by a precision metering valve, and the amount of extension or contraction of a specimen is measured by an LVDT attached to the bottom ram outside the pressure cylinder. The pressure cylinder is filled with a solution of castor oil plus 20 percent methyl alcohol and pressure is generated by compressing the fluid with the upper ram.

The pressure generated in the cylinder is measured from a change in the electrical resistivity of a manganin coil located inside the cylinder. The pressure during a test is controlled within about one percent by controlling the upper ram movement during a test. To ensure constant pressure during a test, the upper ram is driven by the discharge from a precharged accumulator contained within the pressure system. A precision metering valve allows accurate control of the upper ram movement so that its movement is synchronized with that of the lower ram, thereby keeping the pressure in the chamber constant during a test.

The load cells used in the hydrostatic pressure unit are based on a previous design<sup>18,19)</sup> and consist of two concentric cylinders containing strain gages. The outer cylinder contains the active strain gages and is subjected to the load, whereas the inner cylinder contains the strain gages that compensate for pressure and temperature effects. The load cell is calibrated under pressure by a spring calibration technique<sup>20)</sup> to account for the effect of hydrostatic pressure on the output of the load cell.

## Results and Discussion

### Strength-Differential Effect

The general characteristics of the deformation behavior of polyethylene and polycarbonate in tension and compression are shown in Figures 1 and 2, respectively, as engineering-stress—engineering-strain plots. These curves were obtained by using a clip-on strain gage to measure specimen elongation in tension tests and two LVDT's 180 degrees apart to measure specimen contraction in compression tests. The S-D effect is obvious for both polymers. The tension tests were continued to fracture, whereas the compression tests were stopped after about 25 percent contraction.

As is well known, polyethylene undergoes very large strains before fracturing. The mode of deformation consists of the formation of a necked region during the drop in load and the subsequent propagation of this neck at a relatively constant load, whereby the original material is transformed into a highly fibrous structure.<sup>21)</sup> The difference in the deformation behavior of polyethylene in tension and in compression is indicated by the blown-up portion of the initial strain region shown in Figure 1. The compression curve does not show yield-point behavior but continuous work hardening during deformation.

In polycarbonate, both tension and compression specimens show upper and lower yield behavior (Figure 2). In the tension

test, a neck forms just after the upper yield point and spreads throughout the sample, with fracture occurring at one of the numerous crazes formed in the necked region.<sup>21)</sup> Because we are primarily interested in comparing tensile and compressive deformation behavior in polymers, our studies are concerned with the low-strain region where necking and barrelling of the test specimen do not affect the stress-strain behavior.

Also included in Figures 1 and 2 are the results from tension tests on specimens that were pressurized to 552 MPa (80 ksi) and held there for 15 minutes prior to testing at atmospheric pressure. The results show that pressurization itself does not change the deformation characteristics of polyethylene or polycarbonate.

Figures 3 through 6 show the true-stress—true-strain curves for the two polymers in the low-strain region, with either change in area or change in length used to calculate the stresses and strains. For comparison, the curves from Figures 1 and 2, based on engineering stress and strain, are also shown. For polyethylene identical curves are obtained up to strains of about 25 percent when change in area or change in length are used in the true stress—true-strain calculations (Figures 3 and 4). For polycarbonate, Figures 5 and 6, the agreement between the two methods for calculating true stresses and strains holds up to a



strain of about 7 percent, which is slightly beyond the maximum in the curves and corresponds to the strain at which necking and barrelling occur during deformation of the tension and compression specimens, respectively. Therefore, change-in-length determinations yield accurate true stress—true-strain curves in both polymers up to the maximum load points in the tension tests. This is the region of the stress-strain curves that is of most concern to this study.

To obtain an accurate determination of the S-D effect, where  $S-D = 2 (|\sigma_c| - |\sigma_t|) / (|\sigma_c| + |\sigma_t|)$  and the subscripts c and t refer to compression and tension respectively, several specimens of each polymer were tested in tension and compression, with a clip-on strain gage used to measure length changes. These results are shown in Figures 7 and 8 for polyethylene and polycarbonate, respectively. The magnitude of the S-D effect is  $5 \pm 1$  percent for polyethylene up to plastic strains of about 8 percent, after which it increases because of the different work-hardening behavior for tensile and compressive deformation. For polycarbonate, the magnitude of the S-D effect is  $14 \pm 2$  percent for plastic strains up to the maximum point, after which it varies because necking and barrelling of the tension and compression specimens occur, making length changes inaccurate for stress-strain calculations (Figures 5 and 6). For polycarbonate, the maximum points in the tension and

compression curves give values of about 12.5 percent for the S-D effect.

Our results for the magnitude of the S-D effect in polycarbonate are in agreement with previous work, which showed an S-D of about 13 percent when the maximum points in the true-stress—true-strain curves for tension and compression tests were used.<sup>22)</sup> Direct comparisons do not appear to be available for the high-density polyethylene used in this study.

If the engineering stress-strain curves are used to calculate an S-D effect, the values obtained are  $21 \pm 2$  percent and  $24 \pm 2$  percent for polyethylene and polycarbonate, respectively. This points out the necessity for accurate strain determinations and the need for true-stress—true-strain data to evaluate the S-D effect.

The values obtained for the elastic modulus of polyethylene and polycarbonate were 1140 and 2350 MPa (165 and 341 ksi), respectively. These values for the modulus of elasticity are at the high end of the range of values reported for polyethylene and polycarbonate.<sup>23)</sup> This is probably a result of our use of strain gages for measuring specimen-length changes occurring in the gage section of the specimens.

#### Volume Changes

The permanent volume changes remaining after plastic deformation of polyethylene and polycarbonate in tension and compression

are shown in Figure 9. The results are similar for tension and compression tests and show that polyethylene undergoes a permanent volume expansion whereas polycarbonate undergoes a permanent volume contraction. The degree of expansion observed for polyethylene is similar to that observed previously for steels.<sup>8,9)</sup> Therefore, these expansions, as well as those observed in the steels, are much smaller than those predicted from the normality flow rule of plasticity theory when the S-D effect is a result of a pressure dependence of the yield and flow stresses.<sup>24)</sup> However, the volume contractions resulting from plastic deformation of polycarbonate have not been observed in metals and are in qualitative as well as quantitative contrast to the normality flow rule, which requires a permanent volume expansion in a material showing pressure-dependent yielding.<sup>24)</sup> Although we have not yet measured the pressure dependence of yield in polyethylene and polycarbonate, previous data in the literature show such a dependency.<sup>2,4,7)</sup>

Because of the significance of the observation of permanent volume contraction resulting from plastic deformation of polycarbonate, several compression specimens of each polymer were deformed in a dilatometer so that the changes occurring during and subsequent to straining could be measured. Although the density measurements appeared reliable, there was the possibility that the liquid medium used for the measurements may have attacked the polymers, although there was no evidence of this.

The results of the dilatometer measurements are shown in Figures 10 and 11 for polyethylene and polycarbonate, respectively. These results are in accord with the density measurements and give similar values for the permanent volume changes remaining after testing and unloading. The dilatometer results also show that the plastic volume change that occurs during deformation, given by the difference in the total volume contraction and the expected elastic volume contraction (extrapolation of the data in the elastic region), is similar in magnitude to the permanent volume changes remaining on unloading. The results obtained for polycarbonate (Figure 11) are in good agreement with some previously reported data for this polymer.<sup>12)</sup>

#### Testing in Hydrostatic Pressure Unit

To evaluate the effect of hydrostatic pressure on the deformation characteristics of polyethylene and polycarbonate, the specimens are tested in a Harwood hydrostatic pressure unit where, because of space limitations, a clip-on strain gage cannot be used for strain measurement during testing. Because an accurate determination of the magnitude of the S-D effect requires accurate strain determination, it is necessary to separate out the machine displacements from those which the specimen undergoes. The LVDT measurements used to monitor ram motion include both the machine and specimen displacements.



To separate the machine displacements from the specimen displacements tension and compression tests have been made on large steel specimens which only undergo small elastic displacements in the load ranges used for the polymers. These test results give the machine displacements throughout the load range used for the polymers and, thereby, can be subtracted from the total displacements measured during a test to obtain the actual specimen displacements.<sup>25)</sup>

Using this technique gives the curves shown in Figures 12 and 13 for polyethylene and polycarbonate, respectively. Comparison with Figures 7 and 8 shows good agreement between the respective curves and the elastic moduli. Also, the magnitudes of the S-D effect calculated from the curves in Figures 12 and 13 are the same as those calculated from the curves in Figures 7 and 8 for the corresponding polymer. Therefore, reliable characterization of the S-D effect can be obtained in the hydrostatic pressure unit and the effect of hydrostatic pressure on the S-D effect can be evaluated.

To protect the polymers from the castor oil plus 20 percent methyl alcohol environment when testing under hydrostatic pressure they will be coated with a RTV silicone rubber coating. This coating is easily applied and cures at room temperatures. It is easily removed from the specimens after testing and has no measurable effect on the mechanical properties.

### Conclusions

The results of this study show that both polyethylene and polycarbonate exhibit an S-D effect at atmospheric pressure. The magnitude of this effect has been carefully determined and is  $5 \pm 1$  and  $14 \pm 2$  percent, respectively, for the polyethylene and polycarbonate used in these tests. The results of the density measurements on deformed specimens and dilatometer tests show that while polyethylene undergoes a small volume expansion, polycarbonate undergoes a volume contraction as a result of plastic deformation. The volume contraction in polycarbonate is in complete disagreement with the normality flow rule of plasticity theory and lends credence to our previous hypothesis from studies on steels, that the classical theory of plasticity should be modified to include pressure-dependent yielding without requiring volume expansion.

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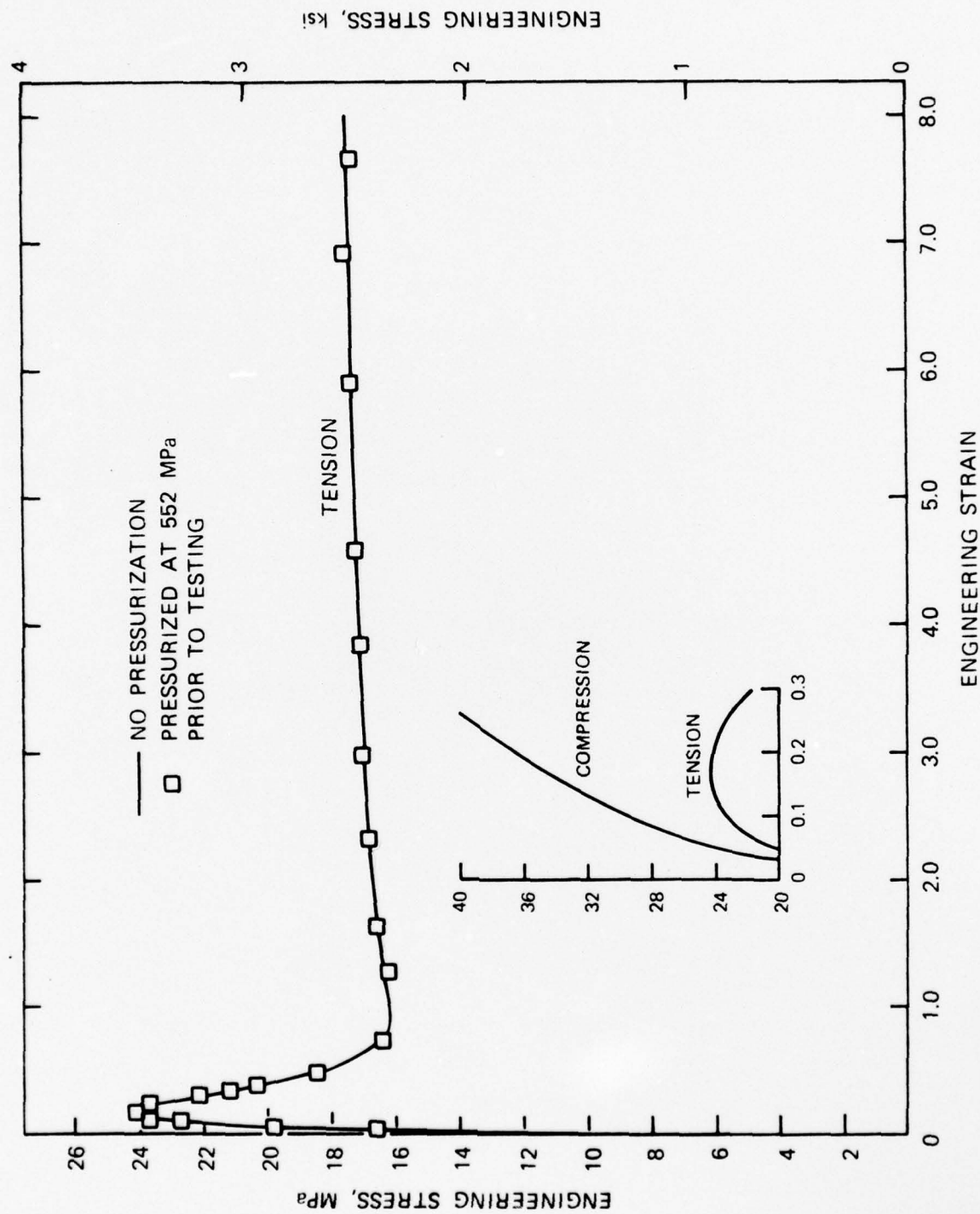
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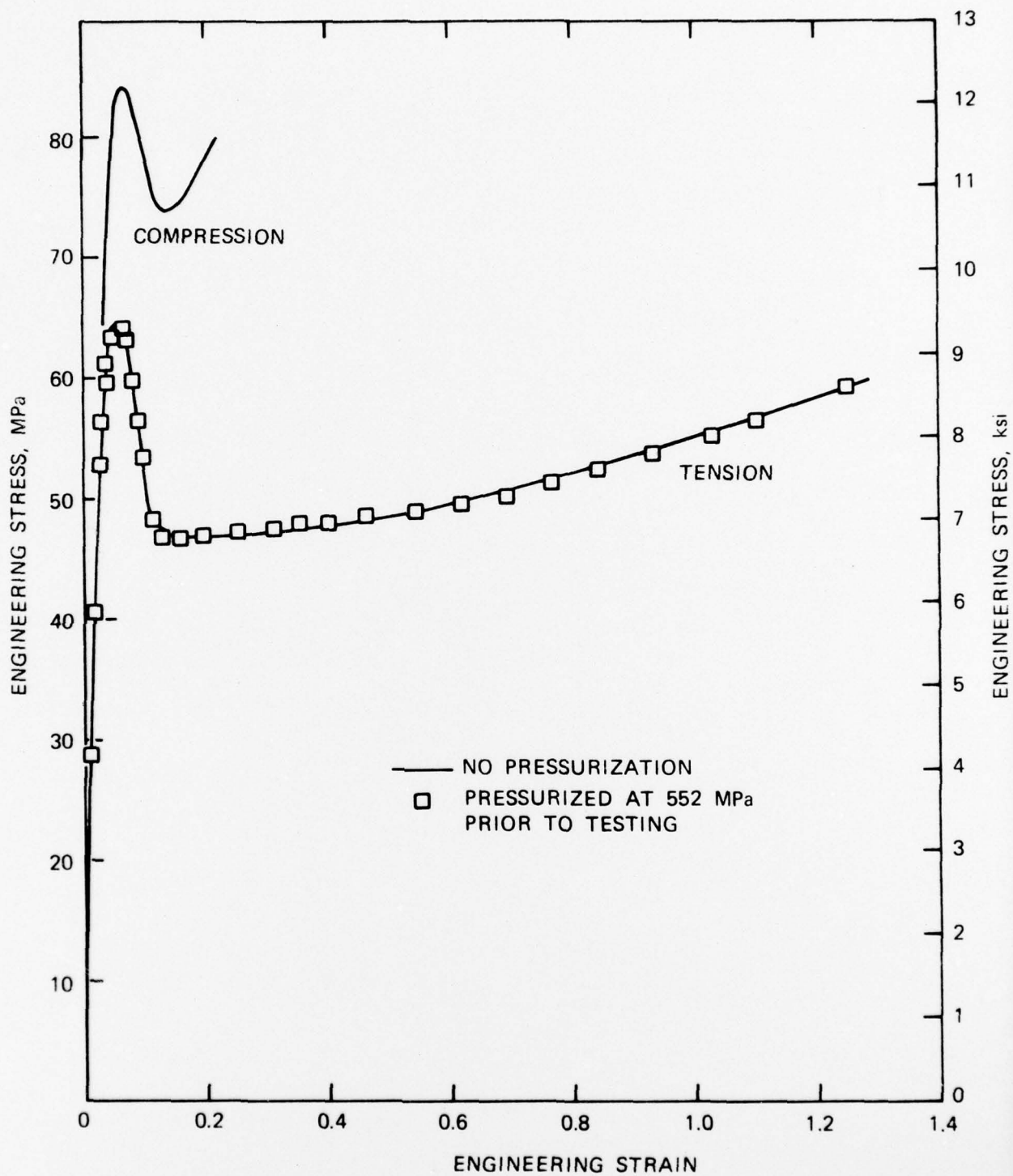
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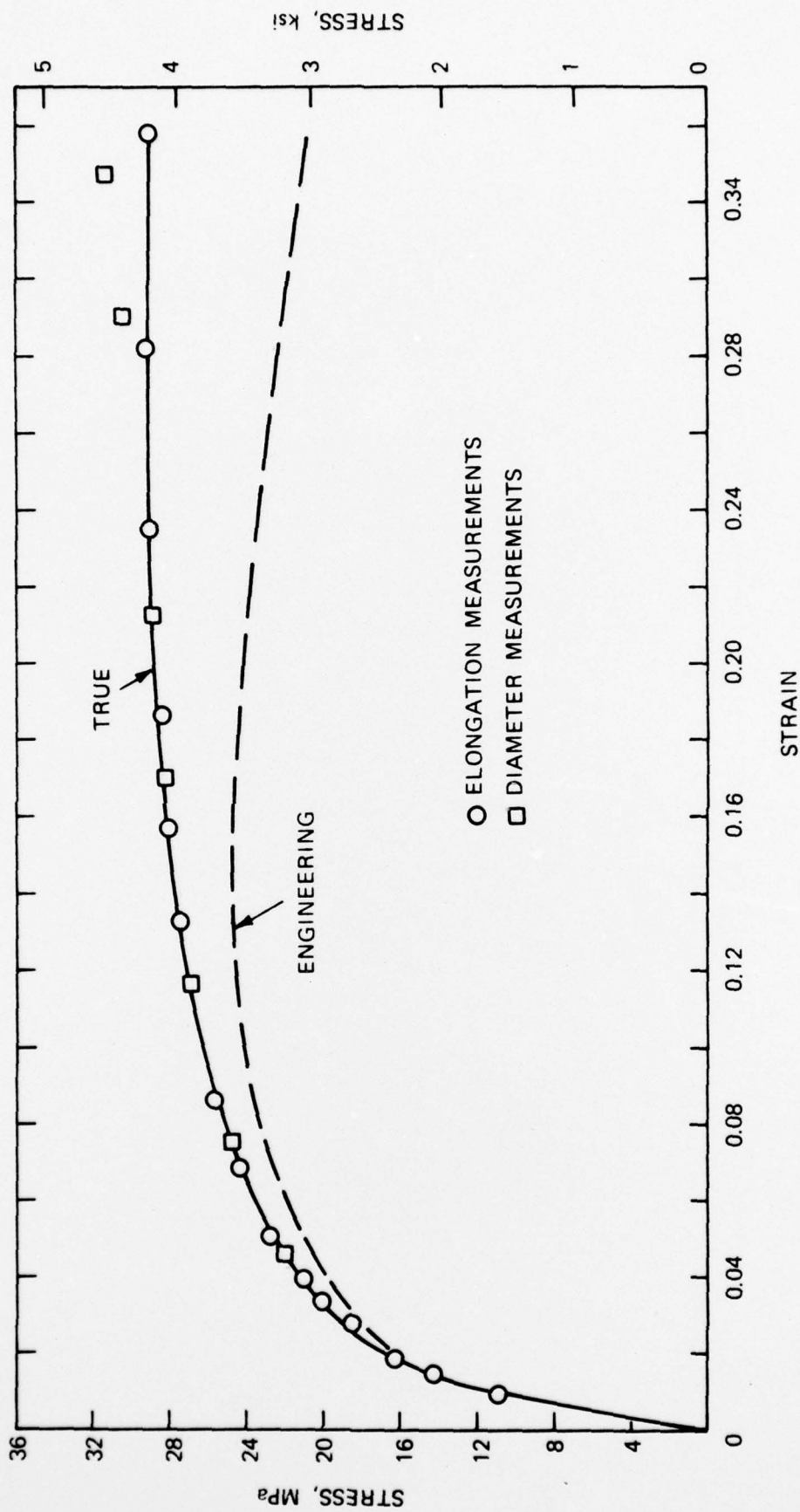
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ENGINEERING STRESS-ENGINEERING STRAIN CURVES IN TENSION AND IN COMPRESSION FOR POLYETHYLENE

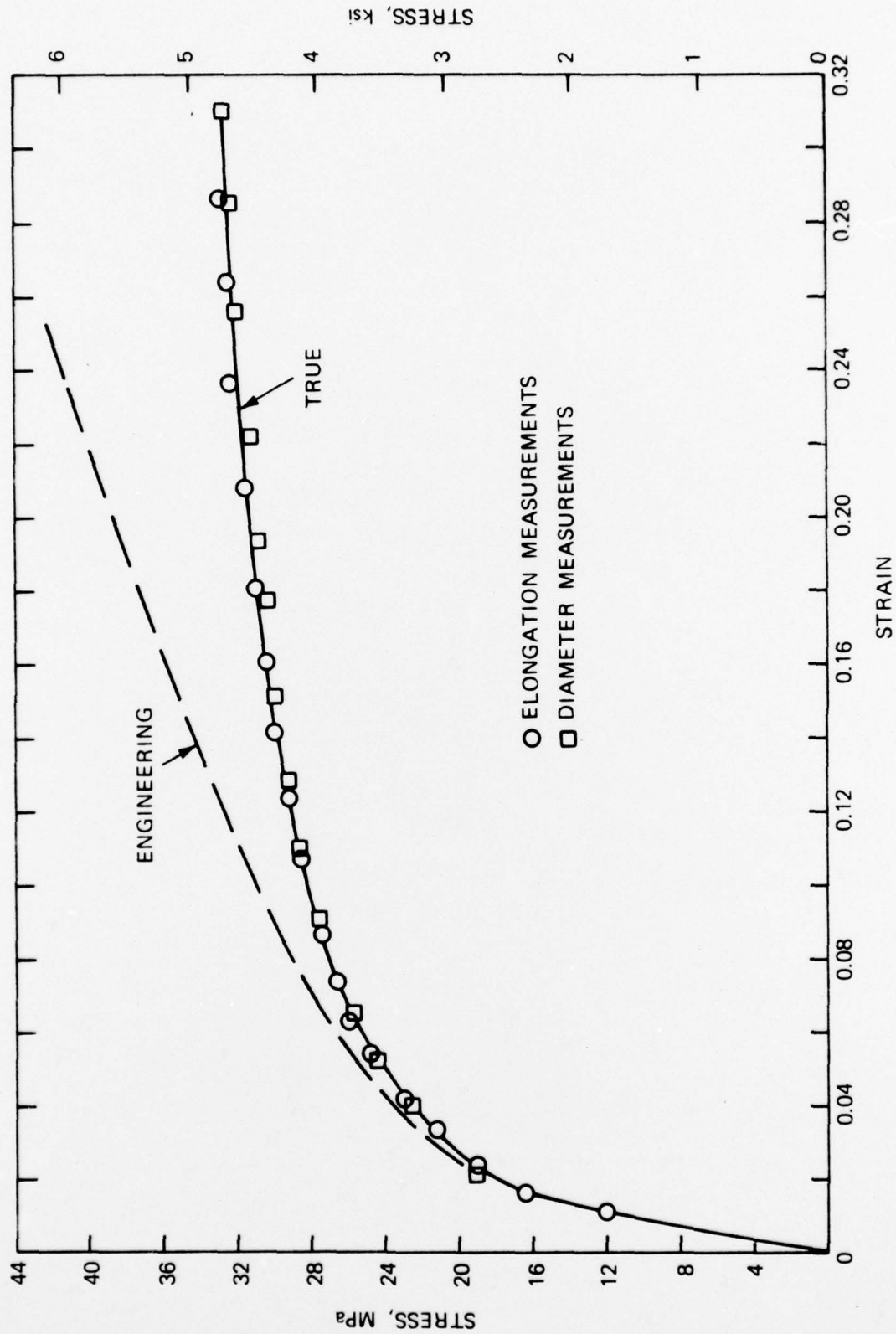


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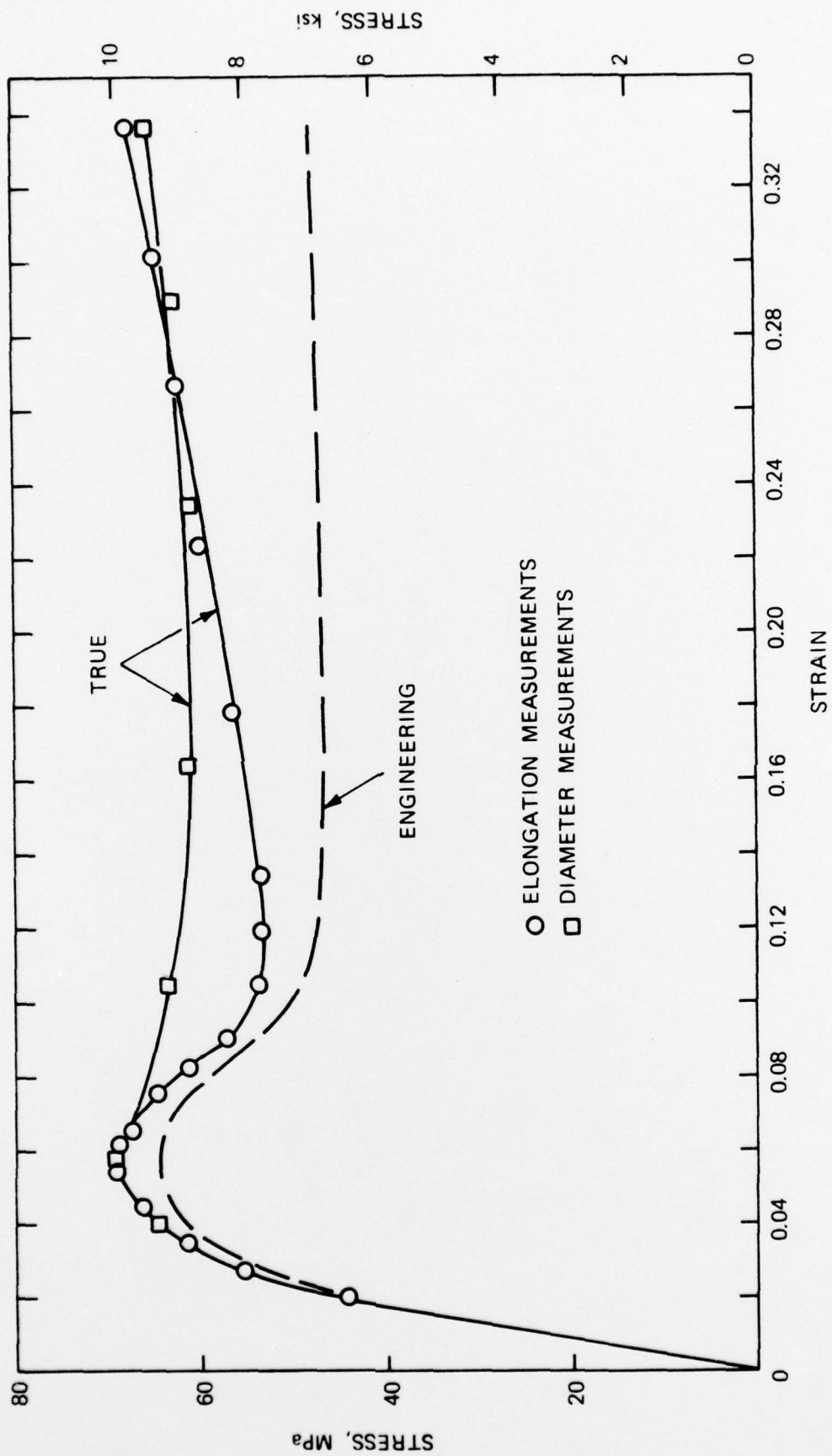


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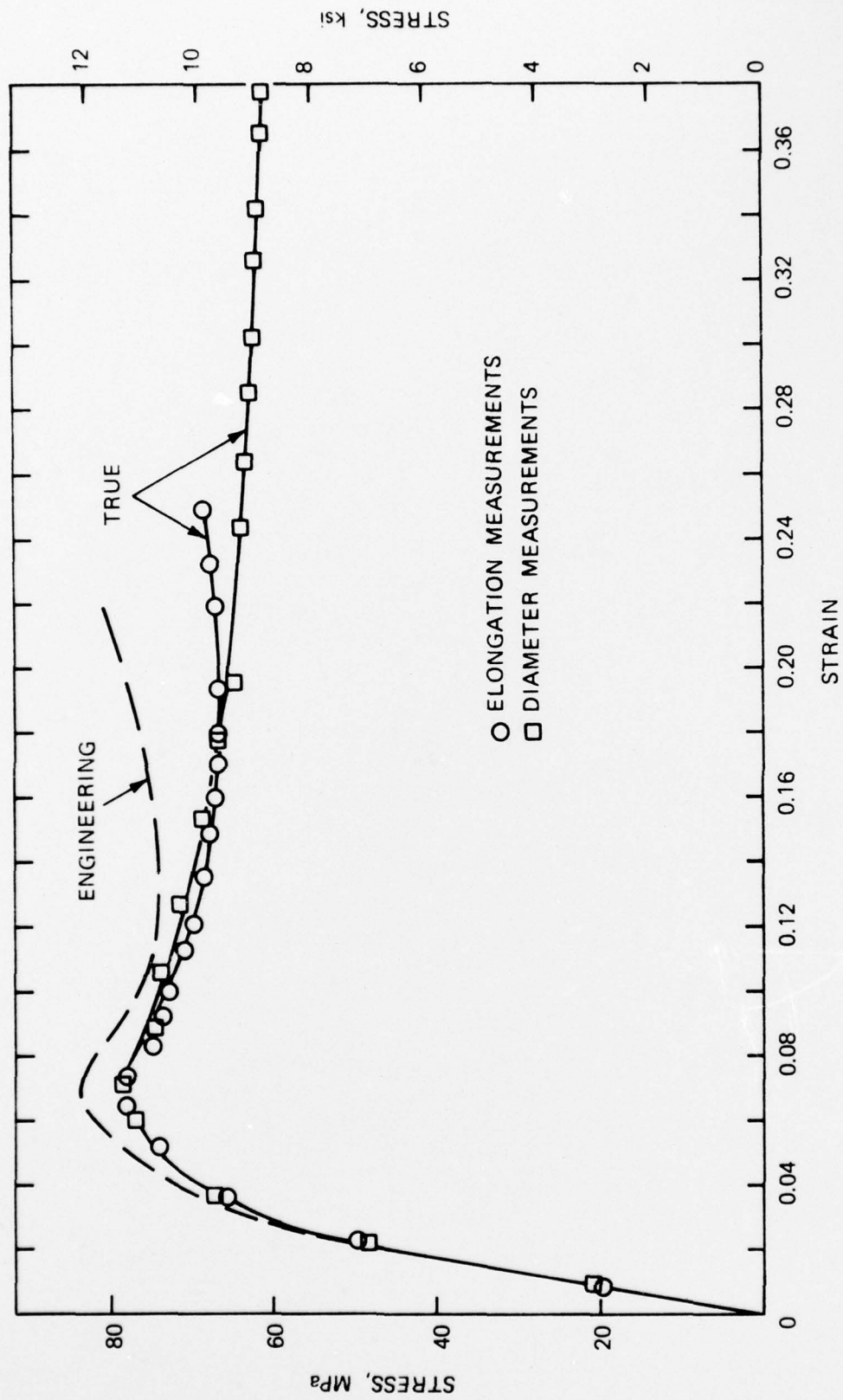




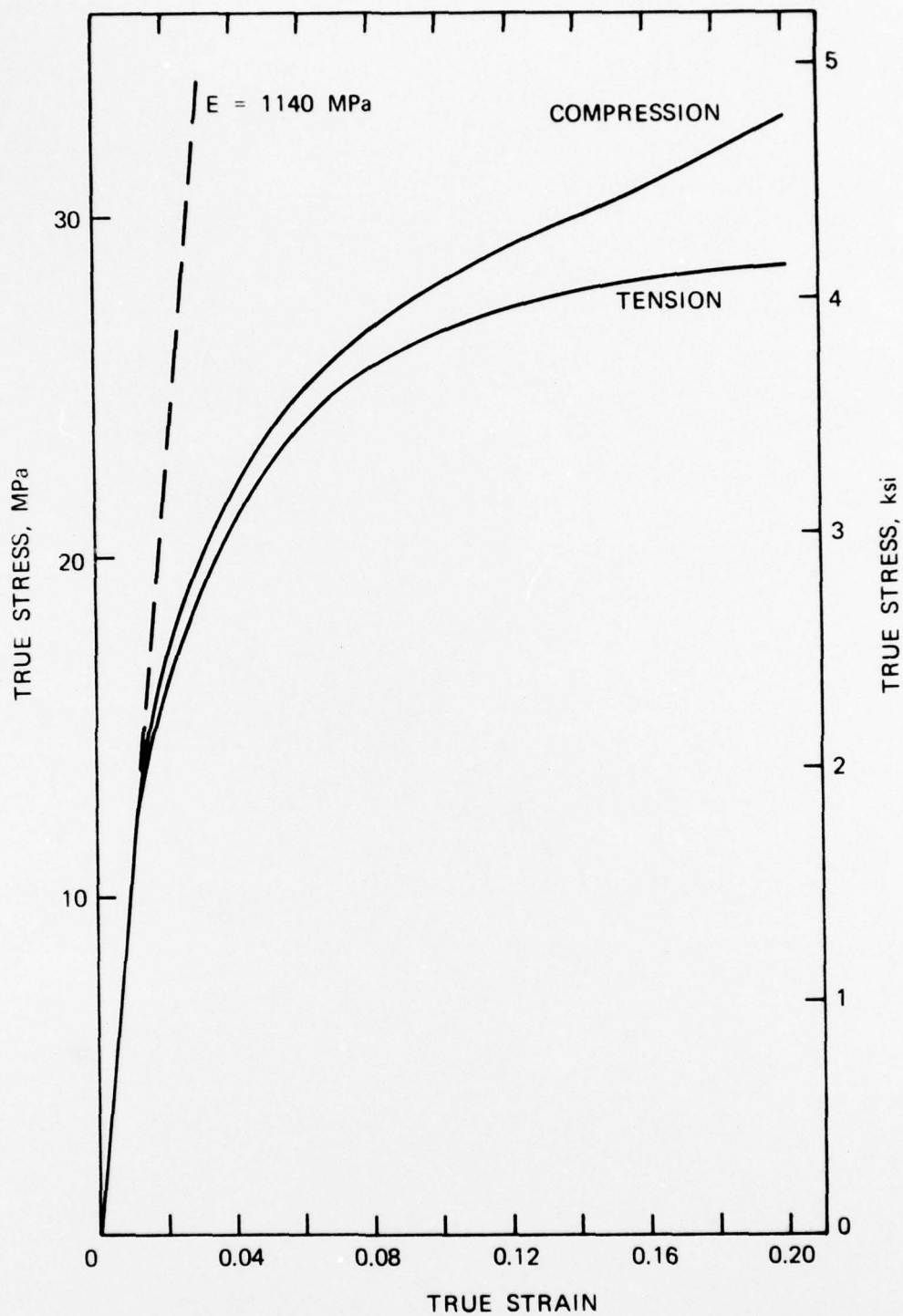
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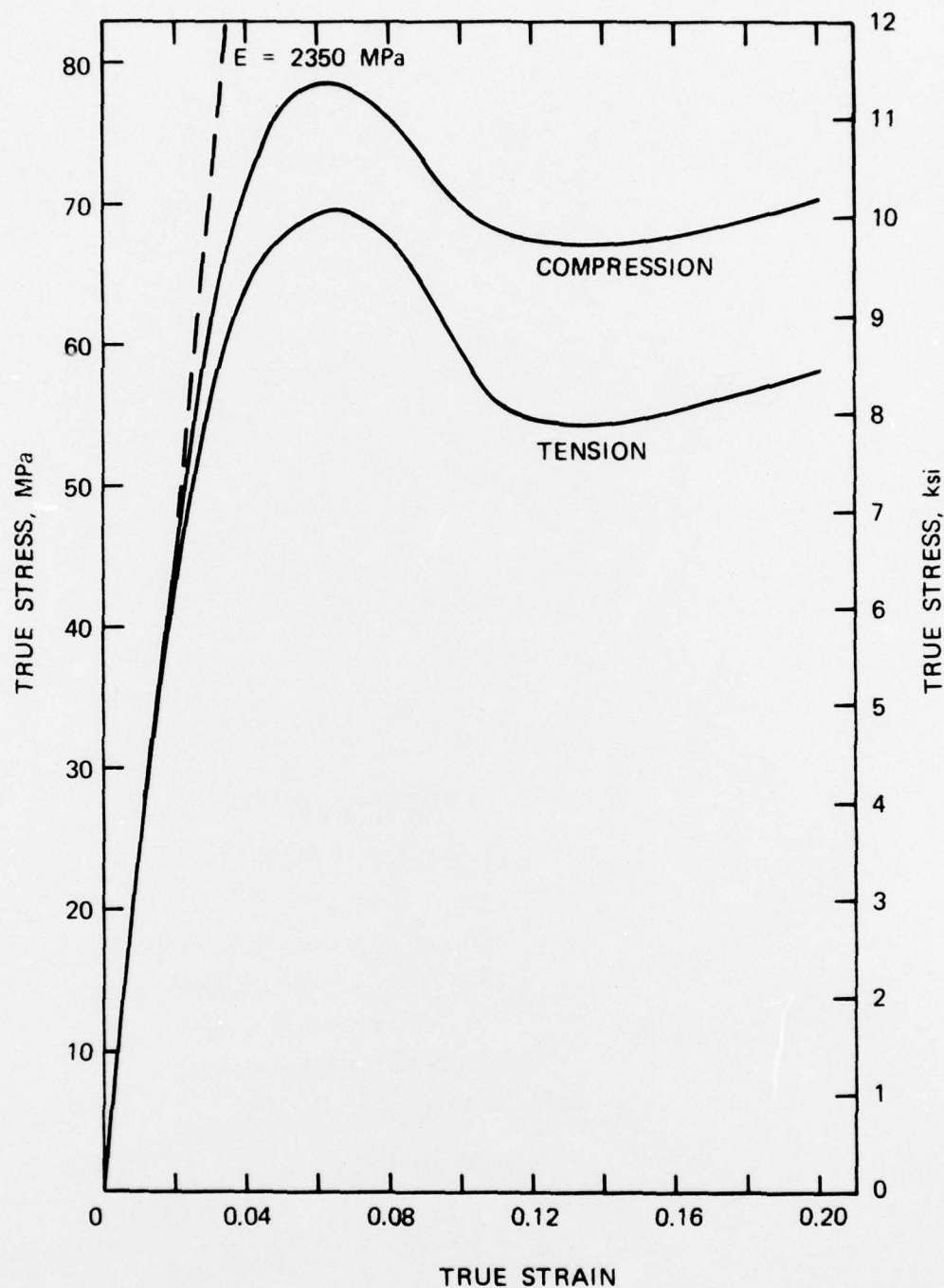


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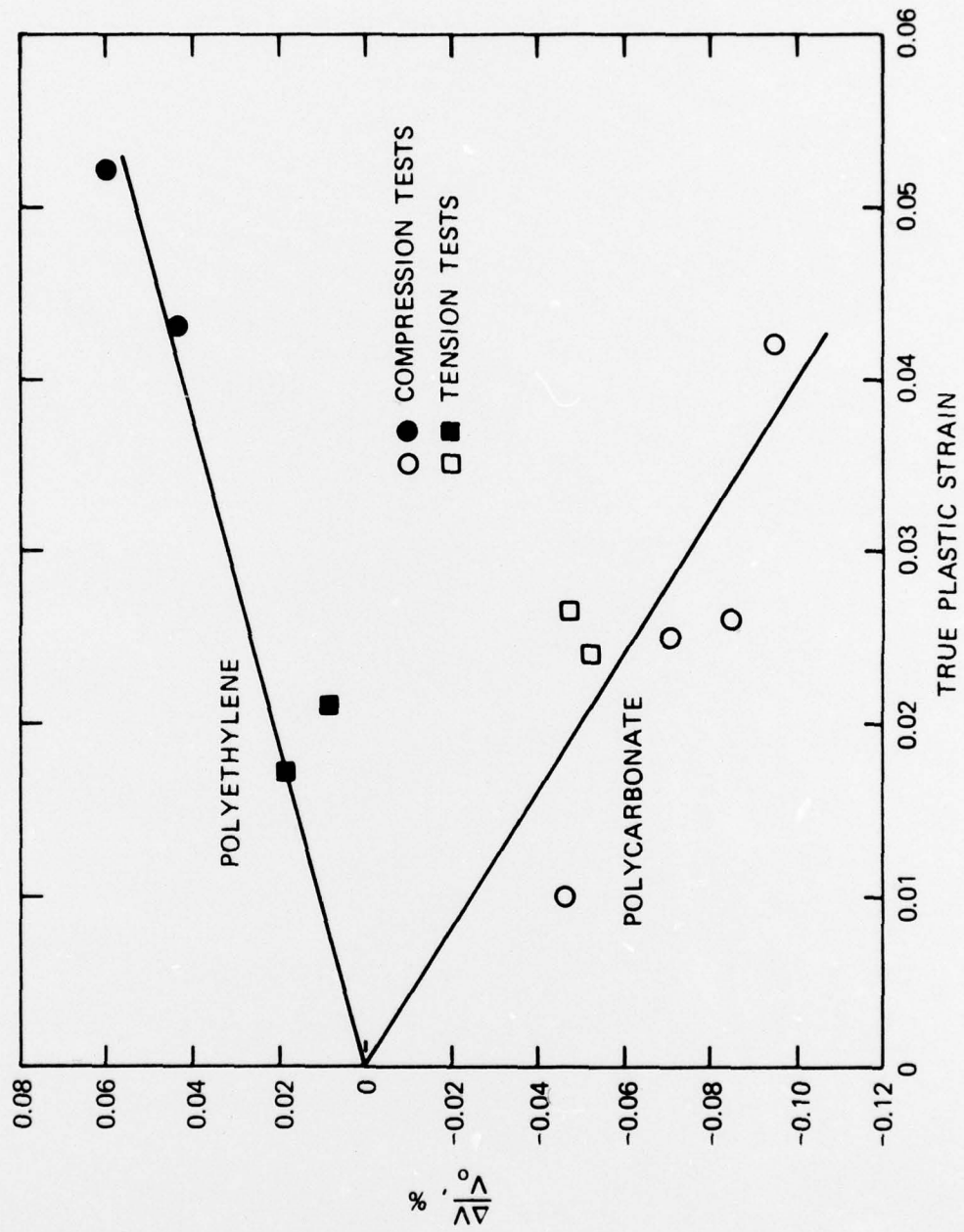


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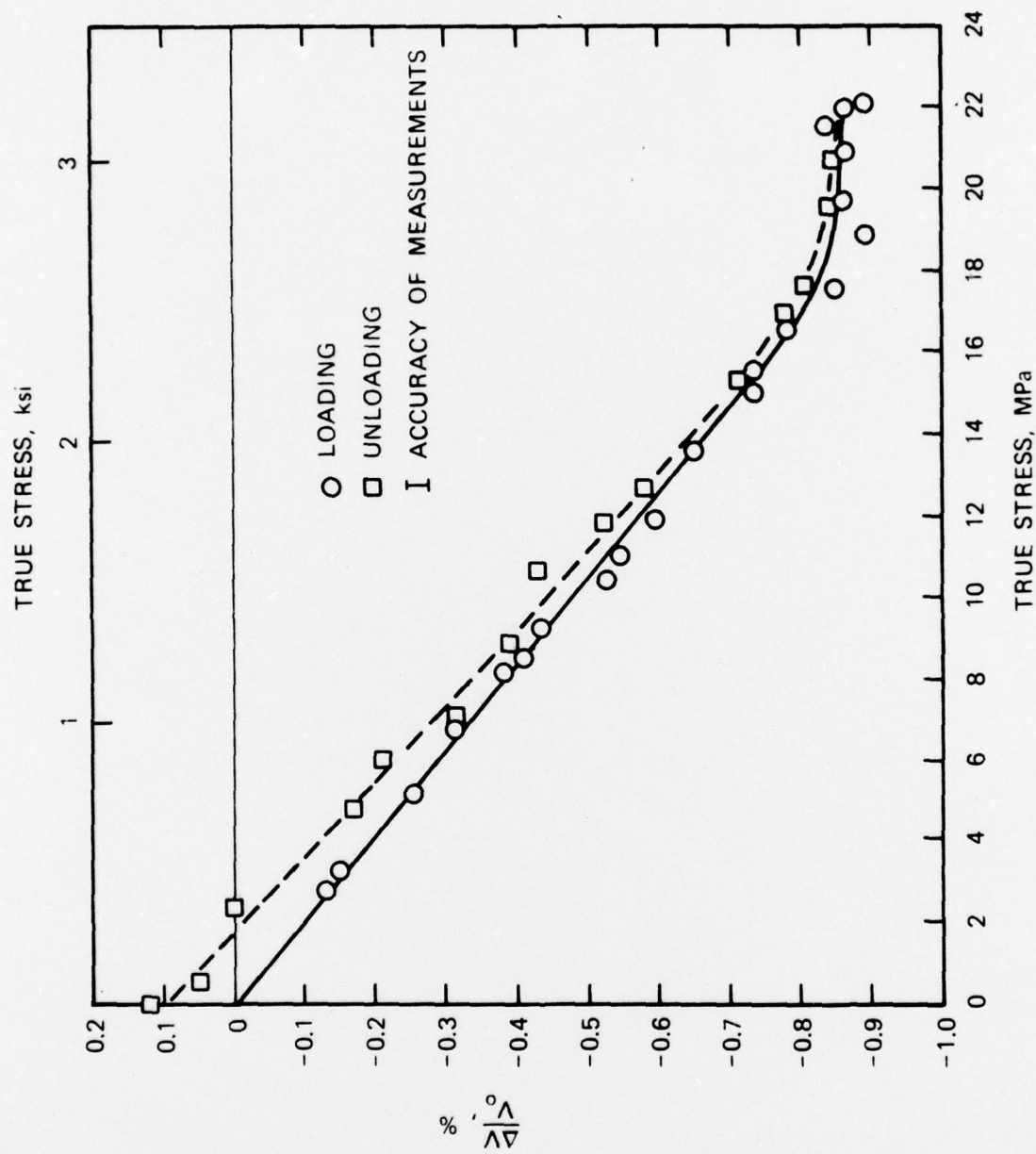




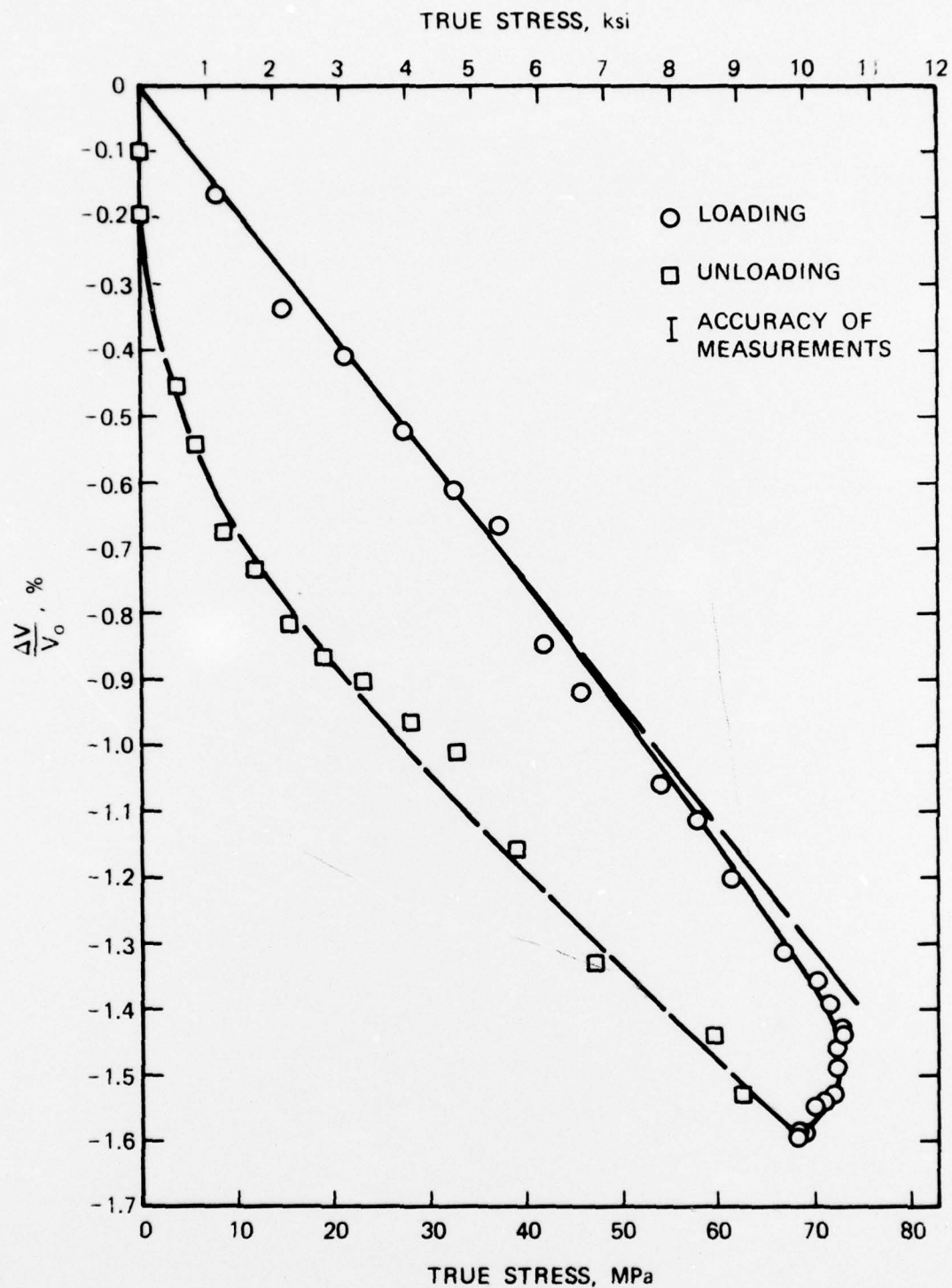
TRUE STRESS-TRUE STRAIN CURVES IN TENSION AND IN COMPRESSION FOR POLYCARBONATE OBTAINED FROM COMBINED TENSION-COMPRESSION SPECIMENS



PERMANENT VOLUME EXPANSION IN POLYETHYLENE AND POLYCARBONATE  
AS A RESULT OF PLASTIC DEFORMATION

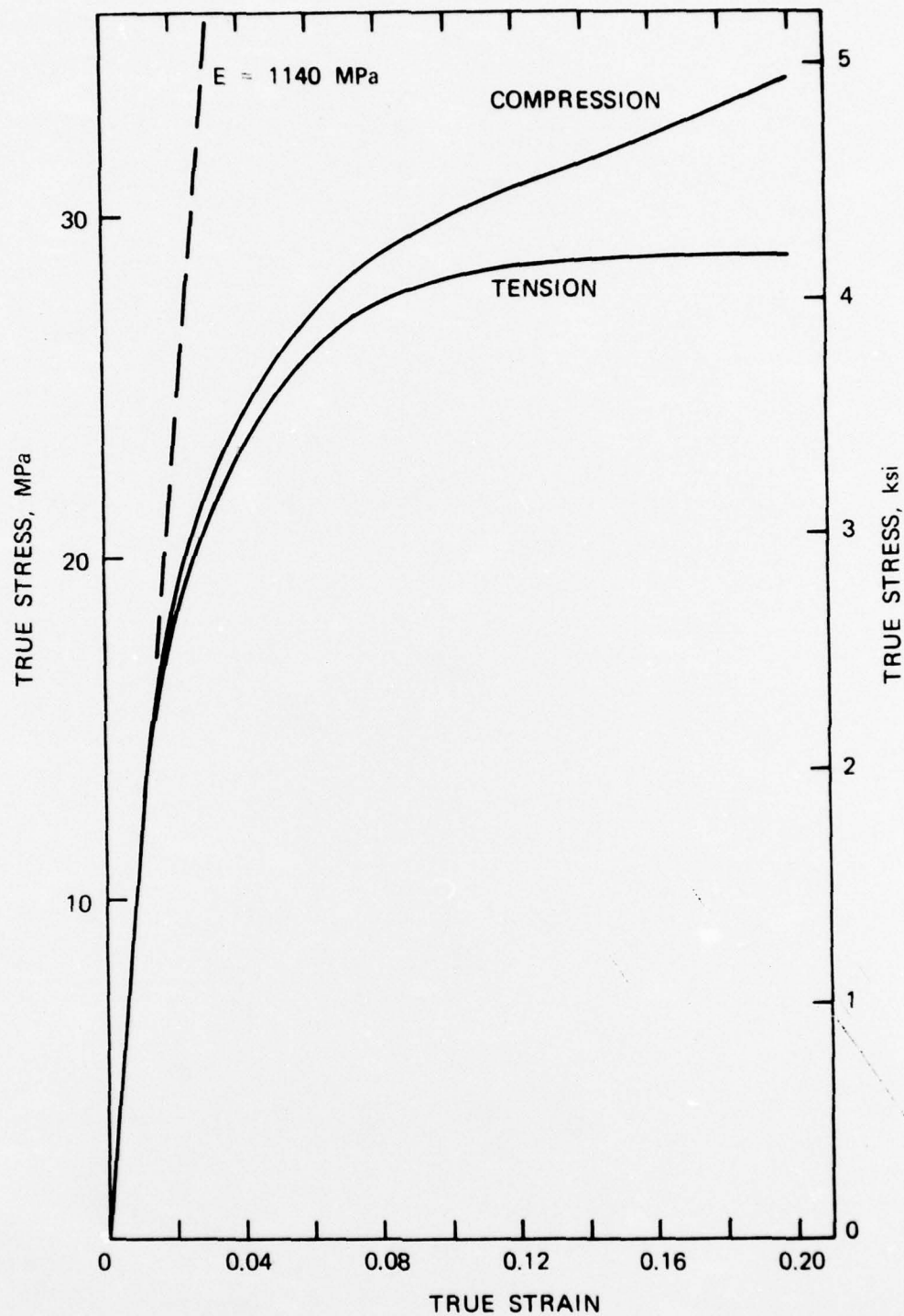


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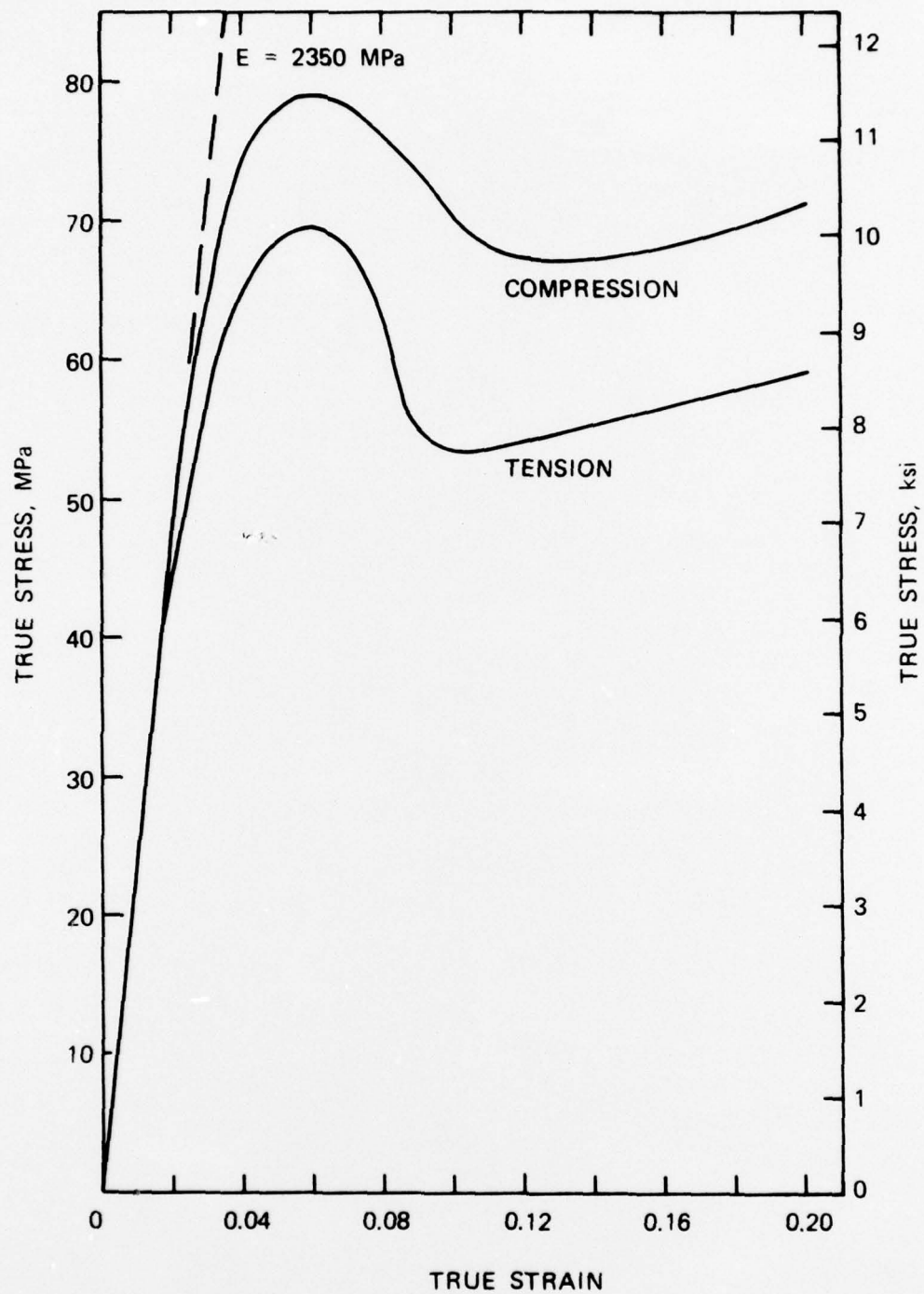


CHANGE IN VOLUME WITH STRESS FOR POLY-CARBONATE DEFORMED IN COMPRESSION





TRUE STRESS-TRUE STRAIN CURVES IN TENSION AND IN COMPRESSION FOR POLYETHYLENE TESTED IN HARWOOD UNIT AT ATMOSPHERIC PRESSURE



TRUE STRESS-TRUE STRAIN CURVES IN TENSION AND IN COMPRESSION FOR POLYCARBONATE TESTED IN HARWOOD UNIT AT ATMOSPHERIC PRESSURE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The stress-strain behavior of high-density polyethylene and Lexan polycarbonate was examined in tension and compression. The results showed that for both the polyethylene and polycarbonate tested, the yield and flow stresses in compression exceeded those in tension, a phenomenon known as the strength differential or S-D effect. The magnitude of the effect was about $5 \pm 1$ and $14 \pm 2$ percent for the polyethylene and the polycarbonate, respectively.		

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Measurements of the volume changes occurring during and resulting from plastic deformation with density determinations and dilatometer tests showed that polyethylene underwent a volume expansion, whereas polycarbonate underwent a volume contraction as a result of plastic deformation. The volume contraction in polycarbonate is in complete disagreement with the normality flow rule of plasticity theory and lends credence to our previous hypothesis from studies on steels, that the classical theory of plasticity should be modified to include pressure-dependent yielding without requiring volume expansion.